Biographies

Willy Bertiger received his Ph.D. in Mathematics from the University of California, Berkeley, in 1976. In 1985, he began work at J 1'1, as a Member of the 'i'ethnical Staff in the Earth Orbiter Systems Group. His work at J]']. has been focused On the use of GPS for high precision orbit determination and positioning.

Sien-Chong Wu received his Ph.D. in Electrical Engineering from the University of Waterloo, Ontario, Canada. He is currently a Technical Group 1 eader in the Tracking Systems and Applications Section at J]'].. He has been involved with the. development of' various tracking, systems for deep-space as well as near-Earth space vehicles, and their applications to precision geodesy. 11 is current interest is in the area of precise positi oning in space using GPS.

Abstract

A number of' missions in the future are planning to use GPS for precision orbit determination. Cost considerat ions and receiver availability make single frequency GPS receivers attractive if the orbit accuracy requirements can be met.

To put a real bound on orbit accuracy at a 700 km alt it ude, GPS data from the GPS/MET experiment on MicroLab 1 are processed as single frequency data. The. G] 'S/MET experiment has a flight TurboRogue receiver on-board making dual-frequency GPS measurements at an altitude of 715 km. The antenna is not zenith pointing, but points off to the side. Orbits computed with the dual-frequency data have an RMS component accuracy of better than 5 cm in the radial and cross track components and better than 10 cm in the along track component as indicated by orbit overlaps and can be used as truth orbits for evaluating the si ngle-frequency deter mined orbits. Single-frequency orbits for GPS/MET have an accuracy of better than 25 cm in radial anti cross track components and better than 70 cm in the along track component.

GPS/MET is not completel y representative of all the possible flight scenarios. Its observing geometry is probably poorer and the data set selected was taken close to a minimum solar cycle resulting in less drag and lower ionosphere err ors. Sonic of these other conditions are examined with covariance and simulation analyses. At the 700 km altitude, covariance and simulat ion show that orbital accuracy at the 20 cm 1 evel i n rad i al anti cross track components and 50 cm in along track is obtainable with a 10 channel single frequency receiver.

Background

The first high quality duai frequency orbiting GPS experiment was launched in August of 1992 on Topex/Poseidon and yielded accuracy of a few cm with operat ional data processing [Bertiger *et. al.*, 1995, Muellerschoen *et. al.*, 1995]. Orbits for Topex/Poseidon are onl y marginal l y degraded when single frequency data are used due to its altitude of 1300 km (above most of the ionosphere) and well modeled dynamics (extensive tuning of the gravity field, low drag, detailed solar pressure and thermal re-radiation models). At lower altitudes, similar accuracy may be obtained without more detailed force modeling with a GPS receiver capable of observing all GPS satellites in view [Bertiger *et. al.* , 1 995]. Accuracy at the cm level is not needed for many missions and a significant cost savings may be realized with single frequency flight receivers. Thus i t becomes important to study the level of accuracy obtainable with single frequency GPS tracking data.

GPS/MET

GPS/MET offers a platform at a lower altitude than Topex/Poseidon in which to validate GPS orbit determination. It carries a dual-frequency fl ight version o{ tile TurboRogue receiver [Meehan, et. *al.*, 1995]. Si ngle frequency performance may thus be validated against higher precision dual frequency determined orbits. In this paper, we wiii first present results on the accuracy of the dual frequency solutions and then compare the orbits obtained using only the data at the 1, i frequency.

GPS/MET Orbit Characteristics

GPS/MET mbits the earth in a near circular orbit at about 715 km. I'able 1 list the main orbital parameters,

Table 1: GPS/MET Orbital Parameters

Altitude	715 km
Eccentricity	.002
Period	99 min
Inclination	70°

Flight Data Characteristics

Data Gaps

GPS fright data collected during the two AS off periods, from June 23, 1995 through July 5, 1995 and October i 1, 1995 through October 22, 1995 were considered for processing GPS/MET in single frequency mode. In comparing to the "*truth*" dual frequency orbits, it is important to eliminate periods with significant data gaps., especial ly when using reduced dynamic tracking methods. Table 2 lists the data gaps in GPS/MET during the test period. Most data gaps were not due to the flight receiver operation, but to other spacecraft systems. Days without significant data gaps include July i - 4 and October 18 - 20.

Table 2: GPS/MET Data Gaps, June 23 - July 5 and October 11 - October 22

Day	Begin Gap hr:min:sec	End Gap hr:min:sec	Length (hrs)
June 23	16:26:0	18:4:10	1.6
June 24	6:51:50	23:54:20	i 7
June 25	6:6:40	10:16:40	4.2
June 25	16:36:20	0:31:50	7.9
June 26	7:2:40	9:21:0	2.3
June 26	15:14:40	15:44:50	0.5
June 26	15:52:0	17:38:0	1.8
June 27	15:5:40	1:45:10	11
June 28	14:21:20	16:1:30	1.7
June 29	15:17:0	15:52:40	0.59
June 30	5:46:50	9:42:40	3.9
June 30	14:31:40	16:21:50	1.8
July 5	14:7:10	17:41:10	3.6
October 11	6:50:50	10:48:50	4
October 12	6:6:20	11:33:0	5.4
October 12	11:42:30	20:49:0	9.1
October i 4	6:15:50	10:10:20	3.9
October 15	5:31:10	9:25:30	3.9
October 16	17:13:10	14:40:20	21
October 2 i	4:21:20	11:26:30	7.1

Number of Satellites Tracked

GPS/MET's antenna is located on the. side of the spacecraft pointing in approximately the anti-velocity direction (Fig. I) during the two AS off periods (June 23 - July 5, **October 11 - 22).** The GPS flight receiver's satellite selection algorithm also allocates two of its 8 channels to tracking satellites below the local horizon for radio occultation experiments. For July 1 - 4 and October 18-20, the average number of GPS satellites tracked during each **5** minute **period** and used for orbit determination was 4.4 (Table 3). The average of 4,4 satellites is less than 6 possible duc to the elimination of data with a signal path lower than 600" km. This cutoff is chosen to eliminate possible excessive ionosphere errors from data with long paths through the ionosphere. Note that the number of satellites tracked is significantly worse than Topex/Poseidon which averages close to 6 with its continuously zenith pointing antenna [Bertiger *et. al.*, 1995].

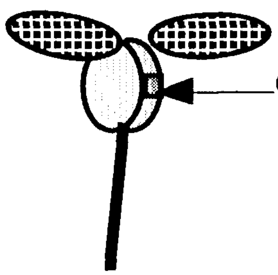

Fig. 1: GPS/MET Spacecraft

Table 3: Average Number of GPS Processed for Orbit Determination

Date	*Average # GPS Tracked*
July 01	**4.49**
July **02**	**4.45**
July 03	**4.50**
July 04	**4.27**
October 18	**4.40**
October 19	**4.45**
[)clobct'20	**4.50**
Average	4.44

Flight TurboRogue Data Noise

GPS pseudorange data at the 1.1 frequency (1'1) will have a thermal noise of about 5 mm when averaged over 5 minutes while C/A pseudoarange is about a factor of 3 larger, 15 mm. The L1 phase data with 1() second averaging has a thermal noise of about .05 mm. In all cases, the flight P] data were smoothed to 5 minute data intervals with the aid of the carrier, The software that currently performs this smoothing eliminates the ionosphere using the dual frequency data, Some other smoothing technique (polynomial fit), would have to be used for true single frequency data. We c1o not believe that this would be a problem and in the worst case a higher data rate could be used. The data type yielding the. best single frequency results was one we call Group and Phase ionospheric Calibration (GRAPHIC) ((1,1 + 1'1) /2)) data type [*Yunck*, 1993]. Since the data noise on **11 is much** smaller than the noise on P1 data, GRAPHIC data will have a data noise of 1/2 of" 1' I noise and an undetermined bias from the carrier phase data. Errors due to the ionosphere cancel in the GRAPHIC data type, since they arc of equal magnitude but of opposite sign on L1 and P1 data.

Truth Dual Frequency Solutions

In order to assess the accuracy of the single frequency GPS/MET orbits, a "best" reduced dynamic [*Wu et al.*, 1991; *Yunck et al.*, I 990; *Bertiger et al.*, 1 995] dual frequency solution was computed and used as the truth solution in comparison to the. single frequency solutions. A "best" reduced dynamic dual frequency solution was determined by processing data from October 11 -22 and increasing the process noise for the reduced dynamic accelerations until a minimum was obtained in the orbit overlap statistics, The overlap statistics for October 16 and October 17 will be dominated by the differences due to the large data gaps on these days and were not **included. These** overlap statistics indicate that the solution has an accuracy of approximately 5 cm in altitude and cross track components and better than 10 cm in along track.

Dual Frequency Solution Strategy

Due to the limited number of satellites tracked by GPS/MET and the. large number of ground stations

Table 4: Average RMS Overlaps October 11-22 (without October 16/17) as a function of process noise level

Process Noise	Average RMS Overlap Radial, Cross, Along Track (cm)			Average Velocity overlap Radial, Cross, Along Track (mm/sec)			Phase Residuals (mm)
() O 0 dynamic	22.8	9.64	87.4	0."/-12	0.101	0.225	37.3
I O I 0100	12.9	7.4	23	().236	0.073	o.106	24.3
2020200	4.99	6.04	9.83	().0762	0.062	0.056	23.5
4040400	4.7	4.29	8.82	0.0683	0.0443	().()566	22.4
80 80 800	4.59	3.57	8.46	0.0647	0.0378	0.0614	21.2
160 1 601600	5.84	4.86	11.2	0.0698	0.0484	0.0934	19.9

available for tracking GPS, the flight data will not add much to the orbit determination of the GPS spacecraft. Si ncc rapid turnaround is also desired the quick-look GPS orbits and clocks [*Muellerschoen et al.,* 1 995] were held fixed in tbc solution for GPS/MET's orbit. The quick-look GPS orbits and clocks are currently available on the internet approximately 18 hours after the last data point. They include 27 hours of data starting at 21 hours and going to 24 hours of the next day. Thus successive data arcs have 3 hours of overlapping data from 21 hours to 24 hours. These GPS orbits generally have a 3-1) RMS accuracy of' about 30 cm during the data arc.

holding all the GPS orbits and clocks fixed, dual frequency 1'-codc and phase data for GPS/MET are processed at a 5 minute rate using flight data from the same 27 hour interval as tbc quick-look GPS orbits. A data weight of 1() cm was used for the dual frequency phase data with a 1.2 m weight for the. dual frequency P-code data. Solved for parameters include spacecraft initial state (position and velocity), drag coefficient, once per-rev empirical accelerations i n the along track and cross track directions, carrier phase biases, and GPS/MET clock. A solution with these parameters wi II be referred to as a dynamic solution. Two iterations arc performed on the dynamic solution to remove any Imn-lineal effects. With the converged nominal state, a further adjustment of all the parameters is made in tbc presence of additional arbitrary stochastic accelerations in the radial, cross, and along track components. The stochastic accelerations have a 15 minute time correlation with a process noise: of $5n$, $5n$, and Son nanometers/sec^2 in radial, cross, and along track components respectively where n is varied by powers of two to search for the minimum overlap.

'1'able 4 shows that the minimum overlaps occur for the process noise at the 80, 80, 800" nanometers/sec^2 level The RMS overlap (RMS difference in spacecraft position and velocity) for cacb pair of days is computed from 2 1 hrs 25 min to 23 hrs 25 min. The 35 mi n tails are deleted from each end of the 3 hours overlap to remove the edge effects inherent in reduced dynamic processing.

Table 5 shows the overlaps for tbc October data and tbc Jul y data without any large data gaps for the best case process noise. It is these orbits that will be used as truth to compare with the single frequency OrbitS.

Single Frequency Data Processing

For single frequency data processing, the solution scenario, adjusted model parameters and process noise model for reduced dynamics were identical to the dual frequency case. The only difference was the data types, data weights, and the level of' process noise. Two different sets of' data types were tried. In one case, the I . l measured phase was processed simultaneously with the Pl pseudorange as independent data types In the other case, the lineal combination of L1 phase. and } ' l pseudorange was formed to eliminate the ionospheric effects (GRAPHIC data, (L1+ **1'1) /2)).**

1.1, 1'1 Processing

Covariance **analysis** (below) as well as results obtained with the EUVE satellite, [*Gold,* 1994a; *GOLD et al.*, 1994b] suggest that processing phase and pseudorange data as independent data types will not do as wc] I as GRAPH IC data processing. The GRAPHIC approach is superior duc to its better handling of ionospheric errors. One day, June 23, was processed to verify this for GPS/MET. The best orbits obtained with 1.1.1'1 (independent) data were at the few metel level foi this clay while orbits determined with GRAPHIC data were below a meter.

GRAPHIC Data Processing

Using the days without significant data gaps as a test set, the reduced dynamic parameters were tuned as i n the case of dual frequency data. A data weight of 10 cm was used foi the 5 minute GRAPHIC data. Tables 6 -- 8 give the results for' the dynamic orbits and reduced dynamic orbits with levels of 5, 5, 50, and 10, 10. 100 nanometel s/see* in the radial, cross, and along t rack components. Accuracy of the solut ions is determined from con iparison to the dual frequency

Table 5: Reduced Dynamic Dual Frequency Orbit Overlaps, Process Noise 80, S(), 800 nanometers/scc² in Radial, Cross, and Along Track

Date	Radial (cm)	Cross Track (cm)	Along Track (cm)	Radial Velocity (mm/sec)	Cross Track Velocity (mm/sec)	Along Track Velocity (mm/sec)
95jun30/95jul01	4.96	2.87	11.2	0.113	0.0334	0.0651
95jul01/95jul02	3.54	1.55	5.87	0.0201	0.0148	0.0551
95jul02/95jul03	4.16	6.93	14.9	0.136	0.0739	0.0666
95jul03/95jul04	4.49	5.97	8.61	0.0839	0.0503	0.0459
95jul04/95jul05	9.4	15.3	7.92	0.151	0.165	0.111
95oct11/95oct12	2.71	1.66	4.6	0.0451	0.022	0.0669
95oct12/95oct13	2.71	4.53	5.73	0.0298	0.0504	0.0318
95oct13/95oct14	2.51	6.89	8.15	0.07	0.0693	0.0516
95oct14/95oct15	9.3	3.72	10.2	0.11	0.0384	0.0997
!)SoctI5/950cl16	**4.03**	2.31	**7.38**	0.0556	**0.02"/2**	0.0647
950ct17/9soct 18	**5.03**	**2.4**	**9.58**	0.0523	0.0237	**0.0724**
95oct18/95oct19	2.4	2.17	3.82	0.056	().()295	0.0152
95(Jct19/9soct20	7.69	3.68	22.2	0.135	0.0307	0.104
95oct20/95oct2 l	4.04	3.09	7.45	0.0411	().038 I	0.0484
950ct21 /95oct22	5.47	5.28	5.49	0.0521	().()488	0.0595
Average	4.83	4.56	8.87	0.()-/67	().()47"/	0.0639

truth orbits. The 5, 5, 50 results show an accuracy of about 25, 15, and 7(I cm in radial, cross, and along track components.

Table 6: Dynamic GRAPHIC Orbit Comparison to Dual Frequency Troth Orbits

Date	Radial (cm)	Cross Track (cm)	Along Track (cm)	Radial Velocity (mm/sec)	Cross Track Velocity (mm/sec)	Along Track Velocity (mm/sec)
95jul01	23	11.8	77	0.677	0.131	0.253
95jul02	26	13.4	68.9	0.526	0.171	0.283
95jul03	28	17.5	77.1	0.617	0.224	0.31
95jul04	26.7	24.2	70.8	0.565	0.289	0.293
95oct18	18.7	14.9	63	0.566	0.15	0.205
95oct19	26.5	16.4	124	1.2	0.151	0.277
95oct20	29.1	12.8	69.6	0.49	0.134	0.319
Average	25.4	15.9	78.6	0.66	0.179	0.276

Table 7: **Reduced Dynamic GRAPHIC Orbit Comparison to Dual Frequency Troth Orbits, Process Noise level: 5, 5, 50 nanometers/sec^2 radial, cross, along track**

Date	Radial (cm)	Cross Track (cm)	Along Track (cm)	Radial Velocity (mm/sec)	Cross Track Velocity (mm/sec)	Along Track Velocity (mm/sec)
95jul01	31.4	11.1	85.6	0.672	0.122	*0.34*
95jul02	*32.1*	12.1	*79.6*	*() 585*	0.152	0.336
95jul03	*25.2*	19	*74.5*	*0.619*	0.237	*().27*
95jul04	*30.7*	21.2	*83.4*	0.678	*().253*	*().332*
95oct18	*17.7*	*I 2.3*	*54.2*	0.45	0.113	0.193
95oct19	*15.3*	*15.8*	*39.3*	*0303*	0.163	0.158
95oct20	20.6	10.1	55.9	0441	0.101	().2.24
Average	24.7	14.5	67.5	0.535	0.163	0.264

Table 8: Reduced Dynamic GRAPHIC Orbit [comparison to Dual Frequency Truth Orbits, Process Noise level: 10, 10, 100 nanometers/sec² radial, cross, along track

Date	Radial (cm)	Cross Track (cm)	Along Track (cm)	Radial Velocity (mm/sec)	Cross Track Velocity (mm/sec)	Along Track Velocity (mm/sec)
95jul01	31.8	10.9	84.3	0.65	0.121	0.342
95jul02	32.3	11.5	80.3	0,59	0.146	0.338
95jul03	26	13.8	76.7	0.637	0.188	0.279
95jul04	29.7	21.1	80.6	0.655	0.251	0.32
95oct18	23	15.7	67.6	0.555	0.144	0.243
95oct19	16.8	13.5	43.2	0.333	0.142	0.165
95oct20	24.8	12.5	63.6	0.479	0.125	0.27
Average	26.3	14.1	70.9	0.557	0.16	0.28

The amount of process noise that can be added is limited by the data quality and unmodeled systematic error sources. An examination of data residuals can yield some clues as to the limiting error sources. These clues point to multipath errors.

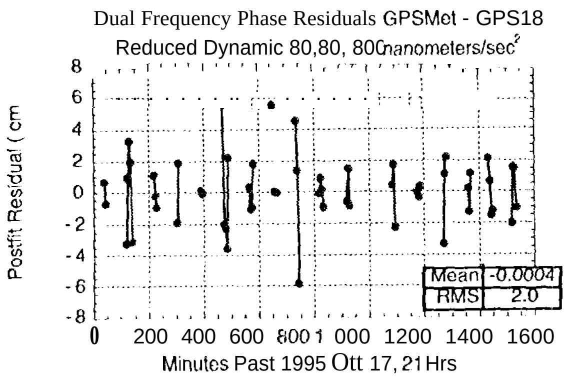

Fig. 2, Reduced Dynamic Dual Frequency Phase Residuals

GPS/MET Post fit Data Residuals

A representative set of post fit residuals was plotted for data taken on October 18 by the GPS/MET receiver. Shown in Fig. 2 – Fig. 4 are the dual frequency phase and pseudorange residuals along with the corresponding best reduced dynamic GRAPHIC postfit data residuals

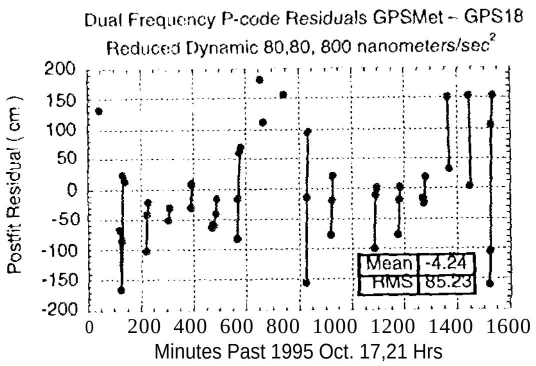

Fig. 3, Reduced Dynamic Dual Frequency Pseudorange Residuals

Assuming P1 and P2 have about the same data noise, dual frequency pseudorange residuals due to either thermal noise or multipath are expected to be about 3 times larger than those for GRAPHIC due to the. dual frequency data combination $(\sqrt{2.54^2+1.542})$. Another factor of 2 results from the fact that

GRAPHIC observables are dominated by the noise in 1'1 divided by 2. So there should be a scale factor of - 6 overall when comparing dual frequency pseudorange residuals and GRAPHIC residuals —- at least for residuals due to thermal effects or multipath. The observed dual frequency pseudorange residu als arc a I itt le more than a factor of 6 larger than the GRAPHIC data residuals. All other error sources that wc are currently aware of do not scale in this way, but would rather be of the same size for all data types (spacecraft position for example). Since thermal noise is believed to be much smaller than multipath noise, we conclude that the most likely dominant error Soil rce for GPS/M I :T data processed with the. GRAPHIC technique is multipath

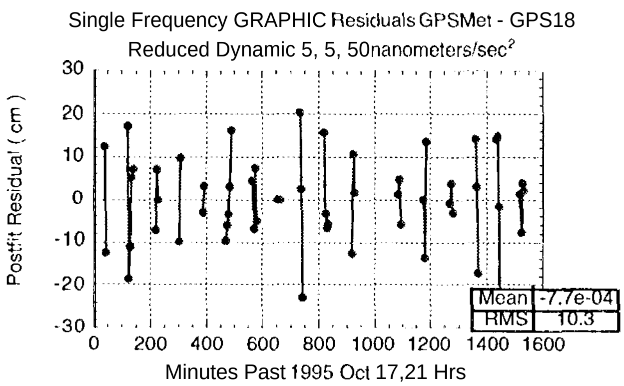

Fig. 4, Single Frequency Reduced Dynamic GRAPHIC Residuals

Covariance Analysis for Low Earth Orbiter (LEO) Orbit Determination' '

The covariance analysis provides a useful complement to the real data GPS/MET studies for several reasons, First, the GPS/MET spacecraft has a different viewing geometry than other spacecraft with zenith point i ng GPS antenna and can sec diff erent combinations of GPS satellite.s. Second, the ionosphere and dynamic errors encountered by other spacecraft may be larger than those encountered by GPS/MET. The following, covariance analysis attempts to provide a conservative assessment of the potential orbit determination capability with single frequency data under a more general observing conditions anticipated for most spacecraft,

The models for the analysis are summarized in Table 9. Note that conservative assumptions WCre made on ionosphere and dynamic errors. The larger dynamic model uncertainties dictate a reduced dynamic tracking on] y. No dynamic tracking was attemped. Two cases were studied.

Case 1: Two antennas, one zenith and one nadir pointing, each limited to observing up to 5 GPS at a time

The two antennas provide a nearly full observing window. Since observations of GPS below local horizon are hampered by strong ionosphere effects, GRAPHIC ionosphere-removing technique is used.

The reduced dynamic orbit determination with GRAPHIC ionosphere-removing technique is, in this covariance analysis. accurate to ().5 m in-track, better than ().2 m cross-track and radial, as shown in Fig.5. Without using GRAPHIC ionosphere-removing technique, the orbit accuracy is only good to 10- 20 m, as shown in Fig.6 (carrier phase data arc de-weighted at 50 cm to account for larger ionosphere effects). The major error source is the ionosphere (Fig.7).

Case 2: Single zenith pointing antenna with a highly restricted ±45° field of view, limited to observing up to 5 GPS at a time

The limited field of view simulates, again on the pessimistic side, a single antenna on a satellite which may turn sideways from time to time, Reduced-dynamic filtering is used to reduce drag and gravity errors

With data noise weights of 1.5 m pseudorange and 1.5 cm carrier phase (de-weighted at 30 cm for ionosphere effects) at 5 minute intervals over 24 11 urs, the orbit can be determined to better than 2 m i n al I three components (radial and cross-track components are better than 1 m), as shown in Fig. 8. With GRAPHIC ionosphere-removing technique, the ionosphere-removed corn bined data are equivalent to phase measurements with 55 cm misc. The orbit is only good to about I S m in-track, 3 m cross-track and radial, as shown in Fig.9.

Table 9. Covariance Analysis Models

Epoch Satellite Orbit Elements	
Semi-major axis	7058 km
Eccentricity	0.0012
inclination	98.11°
Argument of Periapsis	90°
Right ascension	330°
Mean anomaly	0°
Satellite Body	
Body **Shape:**	sphere
Area:	8 m^2
Mass:	817 kg
Tracking Scenario	
Ground tracking sites:	12 global sites
Data types:	L1 pseudorange and carrier phase on LEO L1-L2 pseudorange and carrier phase on ground
Data rate:	every 5 minutes
Data span:	1 day
Filtering Scheme	
Estimated parameters:	LEO epoch position and velocity GPS epoch positions and velocities white- noise clock biases carrier phase biases random-walk tropospheric delays
Error Models	
Data noise:	1.5 m pseudorange on LEO 1.5 cm carrier phase on LEO 0.5 m pseudorange on ground 0.5 cm carrier phase on ground
Ionosphere:	100% Bent Model with an Epoch of March 21, 1992 (near solar max)
Troposphere:	20 cm constant zenith delay; 5 cm/day random-walk variation
Station location:	5 Cm each component
Atmospheric drag:	50 %
Solar radiation pressure:	50 %
Earth re-radiation pressure:	50 %
Gravity:	50% of truncated (50x50) difference between WGS 84 and JGM3 models

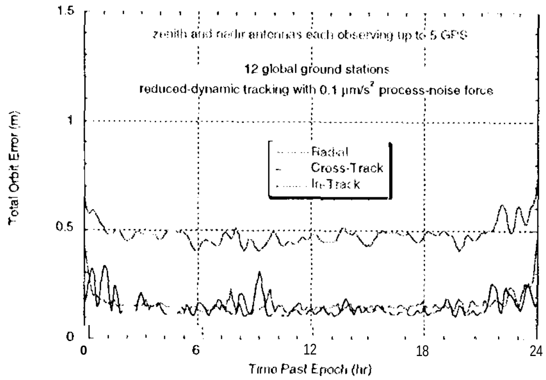

Fig. 5. Results of' covariance analysis with two antennas and GRAPHIC ionosphere removing technique

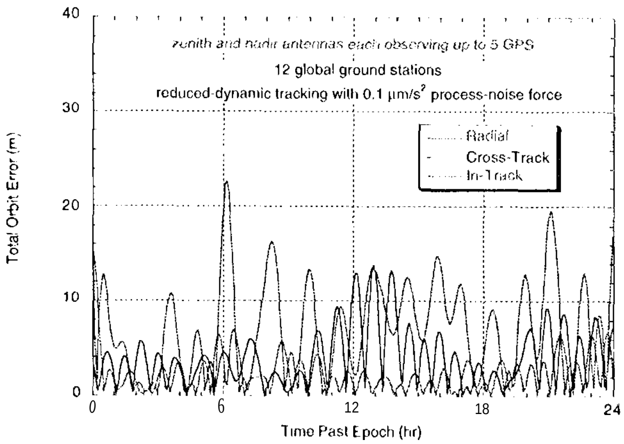

Fig. 6. Results of covariance analysis with two antennas without GRAPHIC ionosphere removing technique

Summary

An RMS accuracy of better than 25 cm in the radial and cross track components and better than 70 cm in the along track component has been demonstrated for single frequency orbit determination for GPS/MET as compared to dual frequency truth solutions using reduced dynamic tracking and the GRAPHIC data combination. The dual frequency truth solutions have an RMS accuracy of about 5 cm in the radial and cross-track components and 10 cm in the along track component.

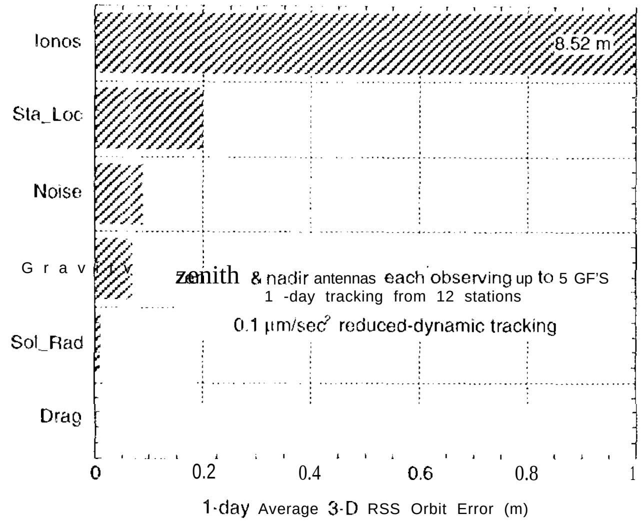

Fig. 7. Error contributions from covariance analysis with two antennas without GRAPHIC ionosphere-removing technique

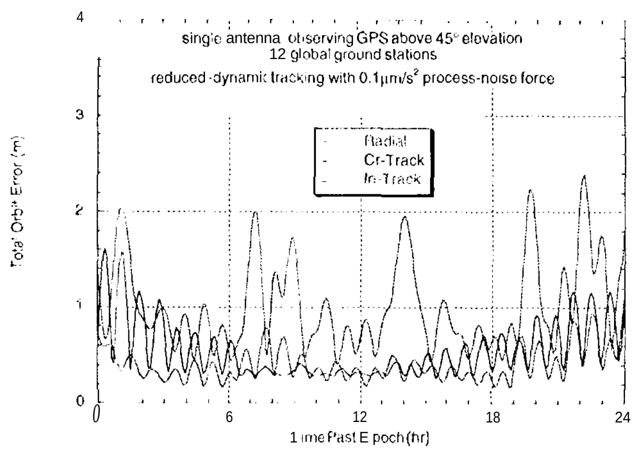

Fig. 8. Results of covariance analysis with single antenna without GRAPHIC ionosphere removing technique

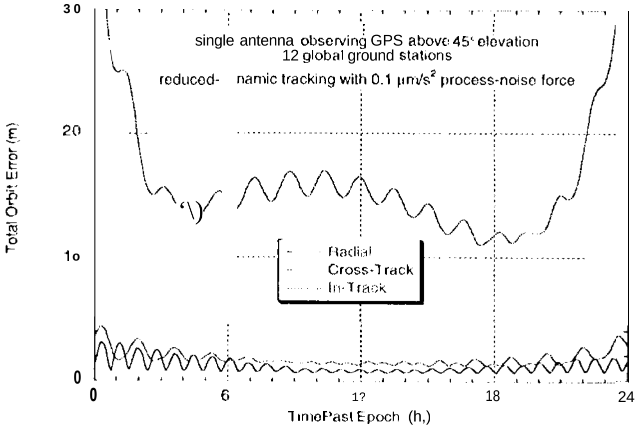

Fig. 9. Results of covariance analysis with single antenna and GRAPHIC ionosphere removing technique

Covariance/simulation analysis indicates that with two antannas simultaneously observing up to 10 GPS satellies and the GRAPHIC technique, the orbit can be determined to 50 cm in the along-track component, better than **20 cm** cross track and radial Components. With a single antenna observing up to 5 GPS satellites above 45° elevation, the ionosphere effects are much lower and GRAPHIC technique is not needed. The orbit accuracy is better than 2 m in the along-track component and better than 1 m in the radial and cross-track components.

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